CONFERENCE PROCEEDINGS

GEOLOGIC CO_2 SEQUESTRATION IN ABANDONED OIL AND GAS FIELDS AND HUMAN HEALTH RISK ASSESSMENT

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Abstract

Sequestration in abandoned petroleum fields has the potential to reduce atmospheric emissions of CO_2 if it is adopted on a large scale. However, sequestration sites may pose risks to people who live in their vicinity. CO_2 release from the sequestration formation through abandoned wells to the vadose zone and then from the vadose zone into people's houses could cause exposure to high levels of CO_2.

CO_2 is different from many other chemicals that may be released into the environment because its effects are acute instead of chronic. Existing literature on the health effects of CO_2 in humans was surveyed to establish risk-based screening levels that could be used near a sequestration site. Two potential screening levels were identified: (1) one person in a million becomes dizzy from inhalation of CO_2 in the basement of a house (3.7780% CO_2), and (2) one person in a million loses consciousness from exposure to CO_2 (6.6744% CO_2).

A hypothetical risk assessment was conducted using a semianalytical wellfield model developed at Princeton University coupled with analytical models of diffusion through the vadose zone and foundation walls. The assessment assumed that a wellfield in Alberta, Canada, was transformed into a sequestration site with an injection rate of 43,200 t-CO_2/day and that a subdivision has been built near the site. The results showed that CO_2 levels on the site will not reach either of the identified screening levels unless the value used for the exchange rate for air in the houses is very small.

Introduction

Subsurface CO_2 sequestration has the potential to reduce atmospheric emissions of CO_2 if it is adopted on a large scale. However, it is possible that sequestration sites will pose a risk to humans or the environment in the vicinity of the injection site. Most current CO_2 injection/sequestration projects are being conducted in the oil industry and, in the United States, are regulated under the Underground Injection Control (UIC) program. Natural and manmade analogs can be used to infer that leakage is a possibility and that leaks could pose a danger to humans and the environment. These analogs include the subsurface storage of natural gas and natural CO_2 leaks.

Natural gas is stored underground during low-demand months for use in high-demand months. Natural gas is typically stored in salt solution caverns, depleted petroleum fields, and aquifers. There are instances where natural gas has leaked from storage sites and found its way to the surface via abandoned wells. One instance occurred in Hutchinson, Kansas, in January 1991. Here gas leaked through a fracture at the Yaggy storage facility and migrated about 8 miles, where it encountered several unplugged or poorly plugged abandoned wells. The leaks to the surface resulted in geysers of brine, bubbling gas, and explosions [Allison, 2001]. The natural CO_2 leak that started after the 1989 earthquake at Mammoth Mountain, California, caused a large tree kill zone [Farrar et al., 1995] and at least one human fatality [Hill, 2000].

Earlier research on subsurface vapor intrusion and gas migration was conducted by Nazaroff and his colleagues [Nazaroff, Offerman, and Robb, 1983; Nazaroff et al., 1985; Nazaroff, Moed, and Sextro, 1988], who looked at indoor air radon concentration and exposure. Johnson and Ettinger [1991] and the ASTM [1995] produced papers that describe models used to investigate volatile organic vapor intrusion. The ASTM [1995] and U.S. EPA [1991; 1996] have produced guidance documents for human health risk for exposure to contaminants. Detailed vadose zone modeling of CO_2 transport has been conducted by Altevogt and Celia [2004] and Oldenburg and Unger [2003]. A simple analytical method for describing the leakage of CO_2 through multiple abandoned wells has been developed by Nordbotten and his colleagues [Nordbotten, Celia, and Bachu, 2004; Nordbotten et al., 2005]. This paper seeks to use a combination of the techniques outlined by these authors along with existing information on the human health effects caused by CO_2 exposure to create a sample human health risk assessment. The assessment looks at the risk of dizziness and the risk of passing out from exposure to CO_2 that has diffused into the basements of houses built on the location of a sequestration site. The Pittsburgh Geological Society has reported an increase in the number of houses with high concentrations of CO_2 in their basements. The Society surmises that the increase is probably due to increased building of new houses over reclaimed coal mines. Basements were chosen because CO_2 is more dense than air, and so it will tend to collect in low-lying areas. During a study in the Alban Hills in Italy Annunziatellis et al. [2003] reported that after a release of CO_2, some cellars were not accessible for a day due to high CO_2 concentrations. The results of the assessment and the other information provided in this paper are used to discuss why the current regulation of CO_2 injection under the UIC program may be inadequate and what may be added in order to better protect human health and the environment.

The Underground Injection Control Program

The creation of the UIC program was a requirement of the Safe Drinking Water Act (SDWA) [1974]. The regulations that make up the UIC program are published in the U.S. Code of Federal Regulations as 40 CFR parts 144 through 148. The program established five classes of wells:

- Class I wells are the most stringently regulated because they are used for the injection of hazardous and nonhazardous waste into formations below the lowest drinking water formation.
- Class II wells are used for brines and other fluids associated with oil production that are injected back into the ground. These wells include saltwater injection wells, enhanced recovery wells, and hydrocarbon storage wells.
- Class III wells are used for the injection of fluids used in solution mining.
- Class IV wells are used for the injection of hazardous or radioactive waste into or above drinking water formations. These wells are banned unless authorized by specific statutes.
- Class V wells are used for the injection of nonhazardous waste into or above drinking water formations

The Class II section of the UIC program currently covers the injection and sequestration of CO_2 because the research is related to the petroleum industry. The fluids that are normally considered Class II fluids include water produced from oil and gas production, drilling waste fluids, fluids used to clean injection lines, workover and stimulation fluids, gas (methane, nitrogen, and CO_2) used for enhanced recovery, fresh water used for enhanced recovery makeup, water containing chemicals or polymers used for enhanced recovery, brine associated with enhanced recovery, waste fluids from methane dehydration and sweetening that are blended with produced water, waste fluids from well cementing, waste oil associated with primary production, and drill cuttings from wells associated with oil and gas production.

In order for a Class II well operator to get a permit, the company must file an application with the director of the UIC program. The application must show that drinking water sources will be protected. In addition, the application must include information on the geologic characteristics of the site, the integrity of the well, the design of the well, the status of wells (abandoned and existing) that penetrate the injection zone in the area of review, and the proposed monitoring program. The area of review surrounding a Class II injection well is defined as either a ¼-mile radius around the well or the computed zone of influence of the injection well if it is greater than ¼ mile. The permits are issued for a specific amount of time that may be as long as the expected life of the well. Wells must undergo structural integrity testing prior to operating and at least every 5 years once they are operating. Wells must not exceed an injection pressure that will fracture the confining unit.

The monitoring requirements spelled out in 40 CFR 144.28 state that the injection flow rate, pressure, and volume of hydrocarbon storage wells must be monitored every day; saltwater disposal wells must be monitored every week and enhanced recovery wells every month. It is possible that the monitoring requirements will be different if the permit for the well specifies other or additional requirements. The monitoring requirements include sampling the injection fluid and analyzing it annually. Operators must report any noncompliance to the U.S. EPA orally within 24 hours and in writing within 5 days. They must also submit an annual disposal/injection report that summarizes the year's injection pressure and cumulative injection volume.

Because the UIC program was set up under the SDWA, the siting criteria for Class II injection wells were formulated to satisfy drinking water protection considerations and not other environmental or human health protection considerations

Human Health Effects from Exposure to CO_2

Carbon dioxide poses the greatest danger to human receptors when there is a high concentration of the gas. Much research has been conducted on the acute health effects of CO_2, and some research has been conducted on the gas's chronic health effects. Chronic exposure studies have shown that at low concentration, 2%, the human body is able to adapt to the increased CO_2 level [Guillerm and Radziszewski, 1979]. The acute health effects range from shortness of breath to death. The effects a person may feel and the speed at which the person feels them are dependent on the concentration of CO_2 to which the person is exposed.

Death

Lethal concentrations of CO_2 can be as low as 8% [International Volcanic Health Hazard Network, 2006]. Occupational exposures, residential exposures, and recreational exposures to CO_2 have all led to fatalities. In most instances in which a death occurred, the actual concentration of CO_2 was unknown but was estimated.

Occupational deaths from CO_2 exposure typically involve workers entering an enclosed space that has a high concentration of CO_2. In some cases, workers died after entering silos and ships' holds; in other cases, fatalities occurred when workers entered wine tanks containing agricultural products that fermented, creating a 25-60% CO_2 atmosphere [Guillemin and Horisberger, 1994; NIOSH, 1976]. In all these cases, exposure led to immediate death or death following a comatose state. The National Institute for Occupational Safety and Health (NIOSH) describes several deaths due to occupational exposure to geologically occurring CO_2: In one incident, a worker died after entering a deep artesian well. In another incident, six workers were killed by high concentrations of CO_2 in a potassium mine [NIOSH, 1976].

Death from exposure on the surface occurs in low-lying areas where CO_2 can collect instead of being mixed into the atmosphere. Typically, low-lying areas include ditches, valleys, and natural depressions. A well-known case in which CO_2 collected in a valley occurred at Lake Nyos in Cameroon in 1986. Volcanic CO_2 bubbled out of the lake and killed 1,700 valley residents [Fink, 2000]. In 1986 a cross-country skier was killed by elevated levels of volcanic CO_2 that had collected in a snow-filled ditch at Mammoth Mountain, California [Hill, 2000].

Loss of Consciousness

Loss of consciousness has been recorded at CO_2 levels as low as 7.6%. Dripps and Comroe [1947] reported that 1 out of 42 people taking part in a study became unconscious after exposure when the concentration reached 7.6%. At higher concentrations, unconsciousness was much more likely. At 10% CO_2, a person may lose consciousness after 10 minutes [International Volcanic Health Hazard Network, 2006]. At 17% CO_2, all participants of a study lost consciousness after 52 seconds, and at 27.9% CO_2, all participants lost consciousness after 35 seconds. At 30% CO_2, it took just 28 seconds for all participants to pass out [NIOSH, 1976].

Other Symptoms

Healthy people exposed to low concentrations, 3% or less, of CO_2 may suffer from shortness of breath during periods of exertion. Concentrations between 3 and 5% CO_2 cause not only shortness of breath but also headaches and increased heart rate. Between 5 and 8% CO_2, characteristic symptoms include the aforementioned symptoms plus rapid breathing, muscular weakness, loss of mental abilities, drowsiness, and ringing in the ears. Between 10 and 15%, a person will also exhibit eye flickering, psychomotor excitation, and myoclonic twitches. At 15%, additional symptoms include increased muscle tone, perspiration, flushing, restlessness, dilated pupils, leg flexation, and torsion spasms. At 20-30% CO_2, tonic and tonic-clonic seizures and convulsions are typical additional symptoms [Dripps and Comroe, 1947; Maresh et al., 1997; NIOSH, 1976].

Threshold Limit Values and Dangerous Concentrations

In the United States, occupational CO_2 exposure is regulated by OSHA, which has set the workplace permissible exposure limit (PEL) at 5,000 ppm (0.5%) [OSHA, 1989]. OSHA's PEL is a time-weighted average over a 40-hour workweek. NIOSH [1976] and the American Conference of Governmental Industrial Hygienists [1971] also recommend a time-weighted average threshold limit value (TLV) of 5,000 ppm for occupational exposure. NIOSH [1976] says further that CO_2 concentrations over 40,000 ppm (4%) are immediately dangerous to human health. In a 1990 technical report, the U.S. Air Force [Carpenter and Poitrast, 1990] found that the occupants of office buildings had the fewest complaints of sickness when the TLV was 600 ppm (0.06%). The Ontario Inter-Ministerial Committee on Indoor Air Quality found that a TLV of 1,000 ppm was best [Rajhans, 1989].

Environmental Effects

Naturally occurring CO_2 leaks give the best evidence that increased soil concentrations can lead to environmental damage. Emissions of volcanic CO_2 to the soil at Mammoth Mountain led to a large zone where all the trees were killed. Farrar et al. [1995] found that in the tree kill zone the CO_2 concentrations were between 20 and 90%, with most locations being above 30%. Plant life has not been the only environmental casualty of naturally occurring CO_2 leaks; animals have been killed as a result of natural leaks. A volcanic CO_2 leak in the Alban Hills in Italy may have led to an oversaturation of the local groundwater with CO_2. A sudden degassing of the CO_2-saturated groundwater led to an incident that killed 30 cows [Annunziatellis et al., 2003].

Human Health Risk Model

Typically, risk-based screening levels are derived from factors related to chronic exposures to contaminants. For example, in a commonly used model described in ASTM E 1739-95 (Equation 1) [ASTM, 1995], the screening level for the concentration in air is based on the amount of time exposed and body weight, among other things. With this model, the levels of risk or maximum acceptable concentrations based on carcinogenic risk or noncarcinogenic hazard can be calculated.

$$RBSL_{\mathrm{air}}\left[\frac{\mu\mathrm{g}}{\mathrm{m}^3_{\mathrm{air}}}\right] = \frac{TR * BW * ATC * 365\,\frac{\mathrm{days}}{\mathrm{year}} * 10^3\,\frac{\mu\mathrm{g}}{\mathrm{mg}}}{SF_i * IR_{\mathrm{air}} * EF * ED} \qquad \text{[Equation 1]}$$

where: $RBSL_{\mathrm{air}}$ is the risk-based screening level for air, TR is the target excess individual lifetime cancer risk, BW is adult body weight, ATC is the averaging time for carcinogens, SF_i is the inhalation cancer slope factor, IR_{air} is the daily inhalation rate, EF is the exposure frequency, and ED is the duration of exposure.

For CO2 it is not helpful to use averaging time or duration of exposure to calculate a risk-based screening level for inhalation, because both factors are for chronic exposure. Instead it makes sense to choose a screening level based on the acute health effects presented in the previous section. The potential important acute health risks to consider are dizziness and passing out, both of which would increase a person's chances of having an accident (such as falling). Plotting data collected by Dripps and Comroe [1947] and Maresh et al. [1997] and fitting the data with straight lines, one can get simple models of risk based on CO_2 concentration. The plot of the data for passing out is shown in Figure 1, and the linear risk model is given as Equation 2

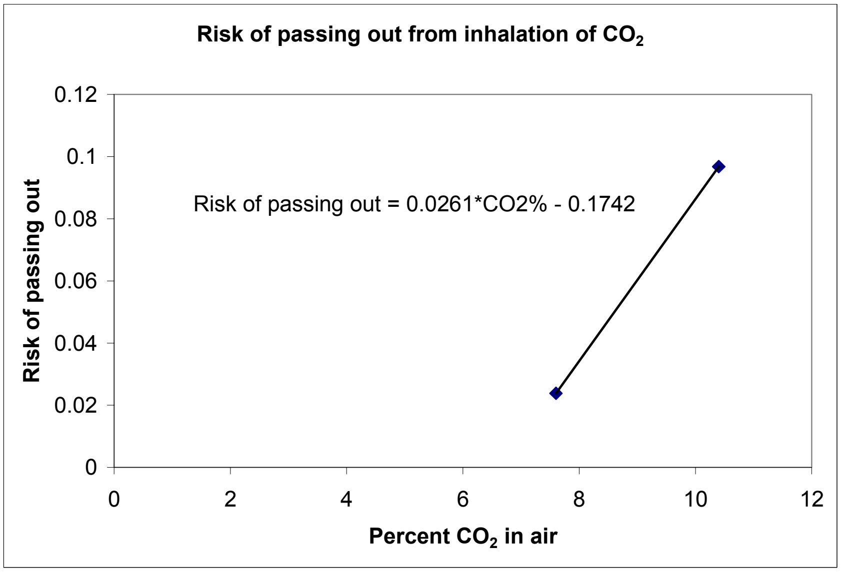

Figure 1 Risk of passing out from CO_2 inhalation exposure

$$RBSL_{air} = 0.0261CO_2\% - 0.1742 \quad \text{[Equation 2]}$$

If one chooses a screening level so that only one in a million people are at risk, the maximum CO_2 concentration for dizziness is 3.7780% and the maximum concentration for passing out is 6.6744%. Both models are threshold models. These models were chosen because it is clear that people can be exposed to some level of CO_2 without acute effects; this conclusion is based on Guillerm and Radziszewski [1979] and the fact that there is an atmospheric concentration of CO_2. The thresholds for the dizziness and pass-out models are 6.6743% and 3.77802%, respectively. (See Figure 2 and Equation 3.)

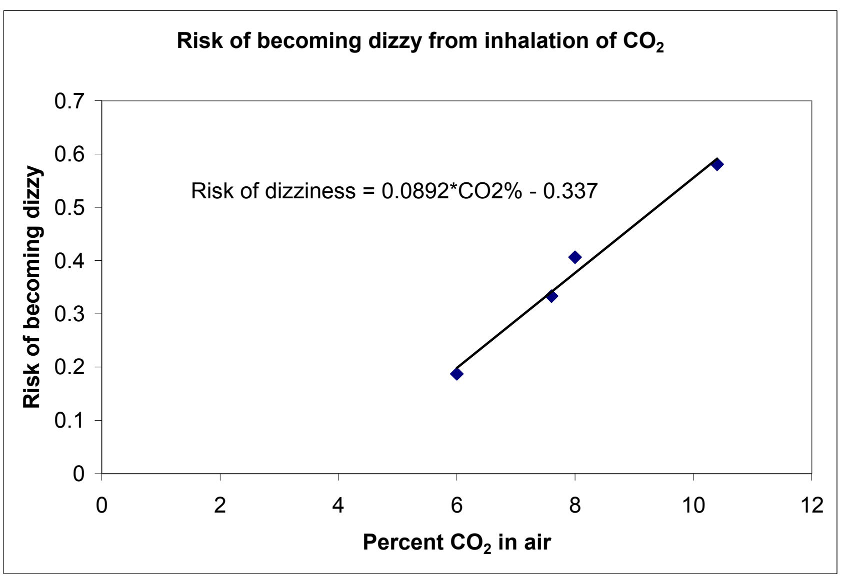

Figure 2 Risk of becoming dizzy from inhalation of CO_2

$$RBSL_{air} = 0.0892CO_2\% - 0.337 \qquad \text{[Equation 3]}$$

Subsurface Transport Model

The model that was used in this work to calculate the transport of CO_2 from the injection formation to the vadose zone is a semianalytical model developed by Nordbotten et al. [2004, 2005]. The model is capable of calculating leakage of CO_2 from the injection formation through multiple formations containing multiple abandoned wells, where each of the well segments and formations has different transport properties (e.g., permeability). The permeability of the abandoned wells in the model is assigned using a normal distribution with an average of 2.55 x 10-8 m^2 and a standard deviation of 1.08 x 10-6 m^2.

Vadose Zone Transport Model

For simplicity the transport of CO_2 through the vadose zone was assumed to be by diffusion only for these calculations, and differences in density of CO_2 and air were not taken into account. A three-dimensional analytical solution of Fick's law was used to calculate the concentrations of CO_2 between the tops of the wells and the foundations of the basements on the properties [Carslaw and Jeager, 1959].

$$C_{\text{soil}} = \frac{1}{4} C_0 erfc\left(\frac{X}{(2Dt)^{1/2}}\right) erfc\left(\frac{Y}{(2Dt)^{1/2}}\right) erfc\left(\frac{Z}{(2Dt)^{1/2}}\right) \qquad \text{[Equation 4]}$$

In Equation 4, C is the concentration of CO_2 outside of the house foundation on the property, C_o is the concentration of CO_2 at the top of the well, X, Y, and Z are the distances between the top of the well and the properties in the X, Y, and Z directions, and D is the effective diffusion coefficient for CO_2 in the vadose zone.

The transport of the CO_2 into the basement through the foundation of the house is an analytic solution that was presented by Johnson and Ettinger in 1991. Equation 5 shows the equation that was used; it is a solution for diffusion of a contaminant through a foundation when the foundation is adjacent to the contaminant. In this equation, C_{basement} is the concentration of CO_2 in the basement air, C_{soil} is the CO_2 concentration of the soil, D^{crack} is the diffusion coefficient for CO_2 through the cracks in the foundation, A_{crack} is the total area of the cracks in the foundation, Q_{building} is the air exchange rate for the basement (the volume of the basement multiplied by the overturning rate), and L_{crack} is the thickness of the basement foundation.

$$C_{\text{basement}} = C_{\text{soil}} \frac{D^{\text{crack}} A_{\text{crack}}}{Q_{\text{building}} L_{\text{crack}}} \qquad \text{[Equation 5]}$$

Site Characteristics

The locations chosen for the residences used in this exercise are hypothetical. However, the well locations and the site geology were based on an oilfield in the Wabamun Lake area in Alberta, Canada [Alberta Geological Survey]. In these simulations the field was approximately 30 x 30 km and contained 502 abandoned wells (Figure 3). The injection well was at the center of the field. Due to the large size of the field, it was divided into U.S.-township-sized blocks (4.08 x 4.08 km). Only the block between $X = 0$ and –4,082 m and $Y = 0$ and 4,082 m (Figure 4) was used in the calculation of leakage through the vadose zone and risk to human receptors. This grid block contained 13 abandoned wells. The township-sized grid block in Figure 4 was split further to create a hypothetical subdivision. The subdivision consisted of 9,888 properties. Each property was 38.9 x 38.9 m, which was the average lot size for new houses in the United States between 1977 and 2003 [U.S. Census Bureau, 2004]. The properties were set up in blocks that were 10 properties long and 2 properties wide. Between each block there was a street that was 7.6 m wide. Figure 5 shows a partial map of the subdivision.

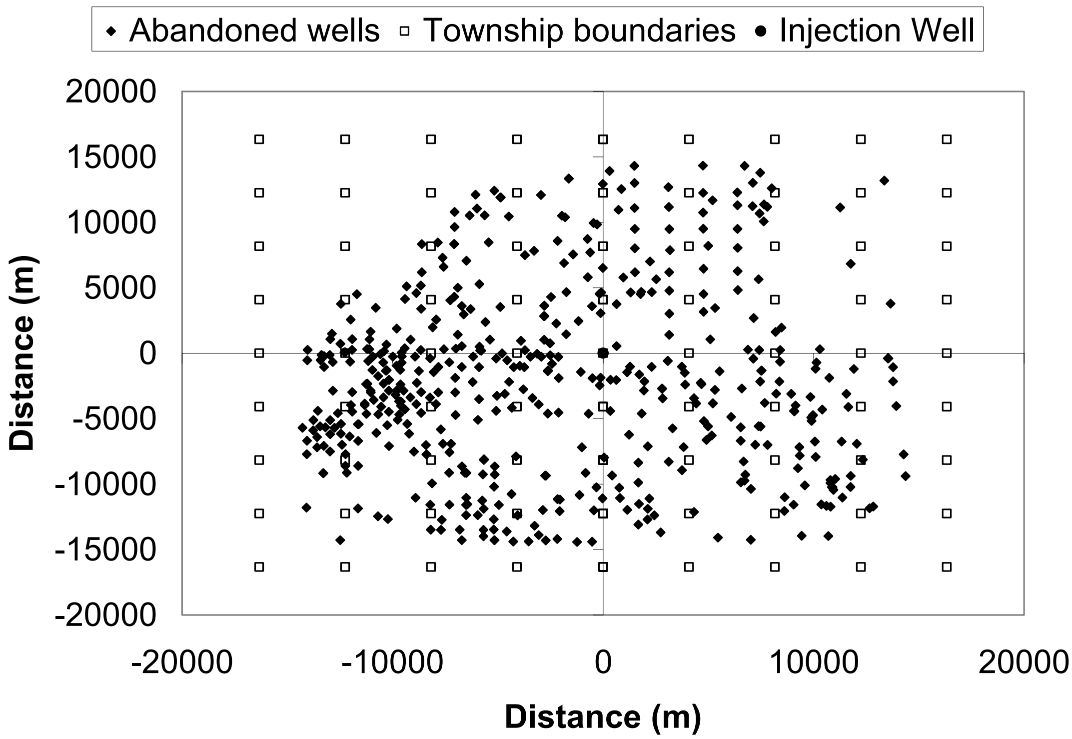

Figure 3 Map showing the location of abandoned wells, township corners, and the injection well used in the analysis.

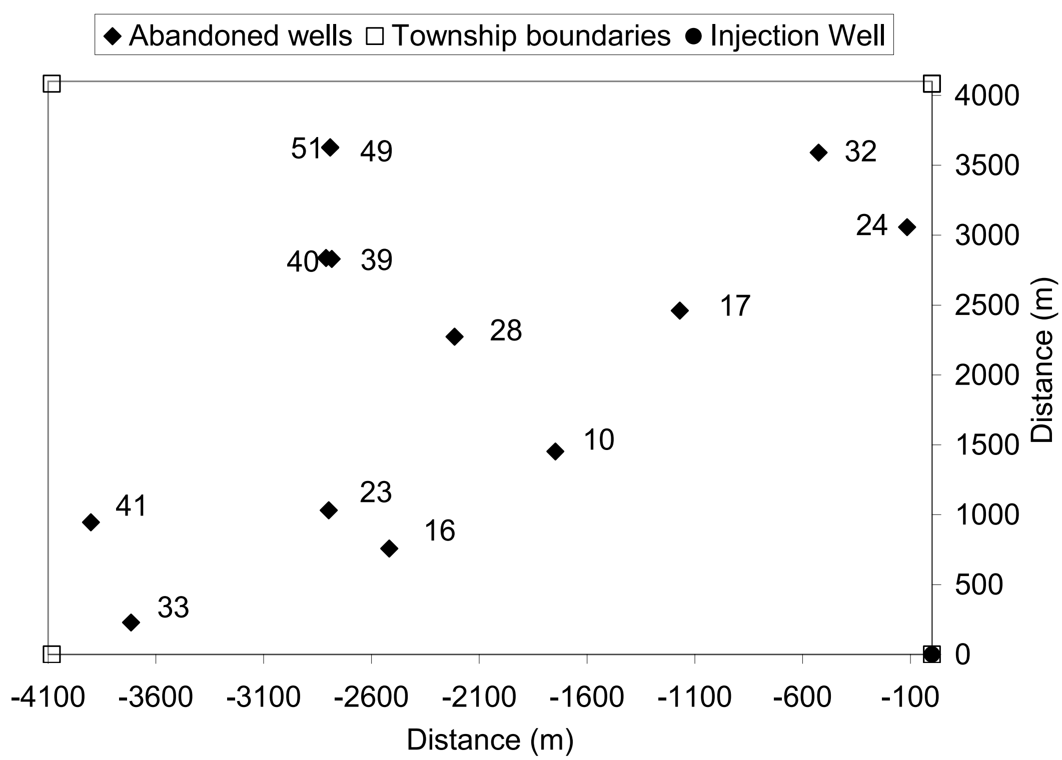

Figure 4 Abandoned well locations used for vadose zone modeling and risk calculations.

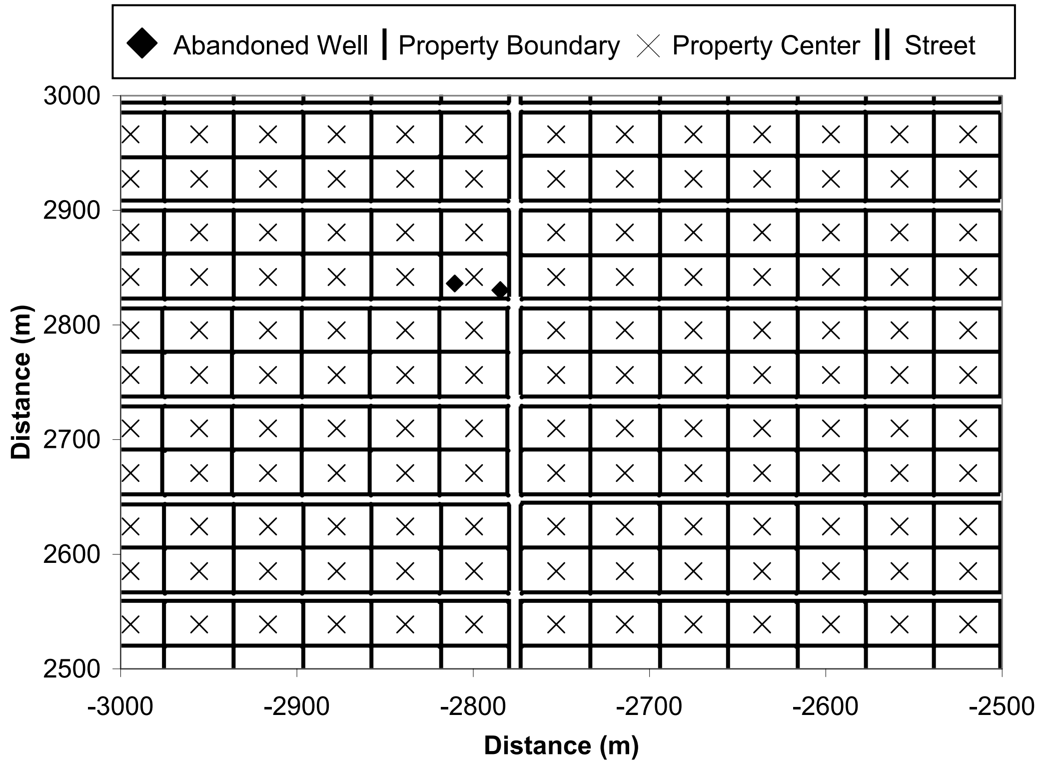

Figure 5 Partial map of property boundaries used in the vadose zone modeling and risk calculations.

The stratigraphy of the site consists of a series of seven aquifers and six aquitards (Figure 6) [Alberta Geological Survey]. The aquifers are either sandstone or limestone, and the aquitards are shale. The injection aquifer for these simulations was the Nisku aquifer, which is a carbonate aquifer. The porosity of the aquifers was assumed to be 0.10, and the permeability of the aquifers was assumed to be 2 x 10^{-14} m^2. The aquitards are shale and were considered to be impermeable. Table 1 summarizes the materials, thicknesses, and permeabilities of each of the formations.

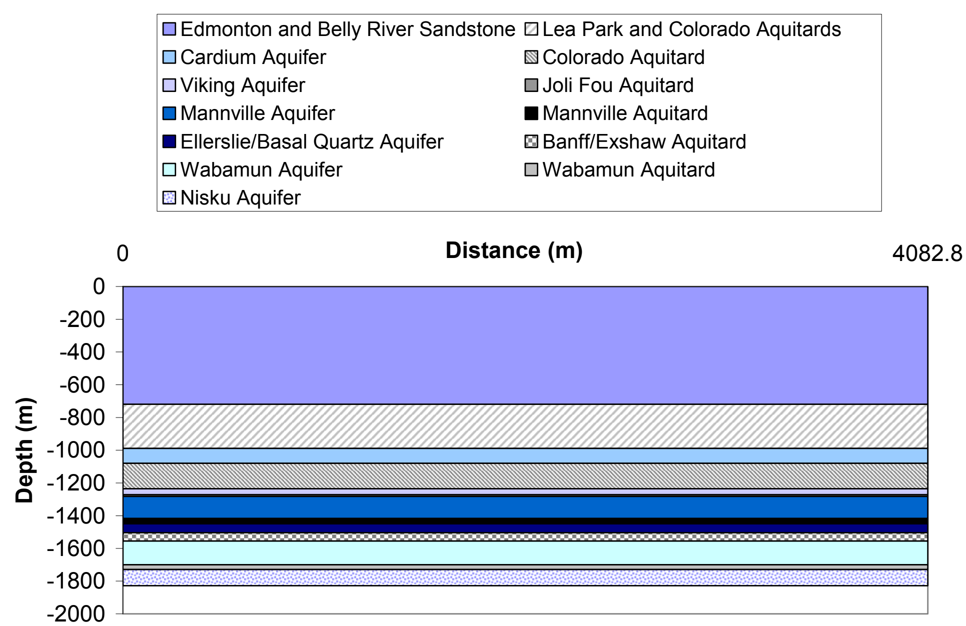

Figure 6 Stratigraphic model used in the wellfield transport modeling.

Table 1 Thickness and permeability data used in the wellfield transport model.

Formation name	Formation material	Formation thickness (m)	Formation permeability (m^2)
Edmonton and Belly River Sandstone	Sandstone	719	2.00E-14
Lea Park and Colorado Aquitards	Shale	270	0
Cardium Aquifer	Sandstone	91	2.00E-14
Colorado Aquitard	Shale	156	0
Viking Aquifer	Sandstone	35	2.00E-14
Joli Fou Aquitard	Shale	11	0
Mannville Aquifer	Sandstone	135	2.00E-14
Mannville Aquitard	Shale	33	0
Ellerslie/Basal Quartz Aquifer	Sandstone	55	2.00E-14
Banff/Exshaw Aquitard	Shale	50	0
Wabamun Aquifer	Limestone	145	2.00E-14
Wabamun Aquitard	Shale	29	0
Nisku Aquifer	Limestone	99	2.00E-14

Each of the wells was assigned a different permeability through each aquitard based on the statistical distribution described earlier. Table 2 shows the permeabilities that were used in the wells.

Table 2 Well layer data for the aquitard layers in the wellfield model.

Geologic formation	Permeability (m^2)						
	Well 10	Well 16	Well 17	Well 23	Well 24	Well 28	Well 32
Wabamun Aquitard	5.39E-08	4.01E-13	6.25E-12	9.44E-13	2.32E-11	5.41E-12	2.77E-12
Banff/Exshaw Aquitard	8.46E-14	1.70E-13	5.54E-15	3.95E-14	1.60E-15	1.62E-15	6.13E-11
Mannville Aquitard	3.49E-15	7.29E-09	2.02E-09	8.85E-13	3.07E-14	5.07E-12	1.19E-13
Joli Fou Aquitard	3.95E-12	6.73E-14	6.31E-14	1.18E-08	1.41E-13	7.66E-13	3.29E-12
Colorado Aquitard	1.24E-12	1.27E-14	3.05E-13	1.52E-11	1.24E-10	1.92E-12	7.61E-12
Lea Park and Colorado Aquitards	2.18E-11	4.27E-13	2.19E-10	8.19E-11	1.09E-10	1.09E-09	2.02E-13

Geologic formation	Permeability (m^2)					
	Well 33	Well 39	Well 40	Well 41	Well 49	Well 51
Wabamun Aquitard	5.30E-13	4.79E-12	1.24E-13	1.00E-11	1.12E-14	2.45E-11
Banff/Exshaw Aquitard	5.86E-05	2.54E-14	2.36E-15	8.45E-12	2.62E-12	7.54E-14
Mannville Aquitard	7.23E-12	3.07E-14	7.61E-11	3.92E-14	3.15E-14	3.76E-12
Joli Fou Aquitard	4.69E-13	2.12E-11	7.87E-09	3.94E-12	1.40E-12	2.61E-12
Colorado Aquitard	4.51E-16	4.18E-14	4.85E-13	1.53E-17	2.04E-13	3.41E-13
Lea Park and Colorado Aquitards	5.78E-10	5.21E-13	3.50E-13	2.23E-14	5.51E-12	3.99E-12

The injection rate used for the injection of CO_2 into the Nisku aquifer was 43,200 t-CO_2/day. Z in the three-dimensional diffusion model, the distance from the top of the well to the basement of the property, was 10 m. The coefficient of diffusion in the three-dimensional diffusion model for the vadose zone, D, and the diffusion coefficient for the cracks in the basement foundations, D^{crack}, were set equal at a value of 1.3×10^{-6} m^2/s. This value is based on the value for diffusion of CO_2 in air, 1.65 x 10-5 m^2/s, used by Altevogt and Celia [2004]. Equation 6 was used to calculate the diffusion coefficient for CO_2 in soil from the diffusion coefficient in air, using ε_v equal to 0.261 and ε_T equal to 0.38 [Johnson and Ettinger, 1991].

$$D = D_{air} \frac{\varepsilon_v^{3.33}}{\varepsilon_T^2} \qquad \text{[Equation 6]}$$

The values for the other variables used in Equation 5, A_{crack}, L_{crack}, and $Q_{building}$, were the same as the values used by Johnson and Ettinger [1991]. A_{crack} was set to 13.8 m^2, L_{crack} to 0.15 m, and $Q_{building}$ to 2.92 x 10^{-2} m^3/s. This corresponded to a basement that was 7 x 10 x 3 m, with half (0.5) of the air in the basement being exchanged every hour. The concentration C_o in Equation 4 was calculated from the output of the mass flux F at the wellbore transport code using Equation 7 [ASTM, 1995]. The cross-sectional area of the well, A, was equal to 0.07 m^2 (where the diameter of the well was equal to 0.15 m), the diffusion coefficient, D, was equal to those for the soils and the basement cracks, and the distance above the well was equal to 0.001 m. The values for the fluxes of CO_2 leaving the top of the wells were the average fluxes over the year of interest, either 5 or 20 years.

$$C_o = \frac{Fd}{DA} \qquad \text{[Equation 7]}$$

Results

The concentrations in the soil and the basements of the properties were calculated at 5 and 20 years after the start of injection. After 5 years, none of the properties had basement CO_2 concentrations above either risk level. The largest leaks were around wells 23, 49, and 51. Here the basement CO_2 concentrations were as high as 0.019% near well 23 and 0.014% near wells 49 and 51. Both these values were below the thresholds of the dizziness and the pass-out model, and so there was no risk to any human receptors. Figure 7 shows a map of the basement CO_2 concentrations in the township block that was used for risk calculations. The maximum soil CO_2 concentrations (Figure 8) around wells 23, 49, and 51 after 5 years were 4.70% near well 23 and 3.42% near wells 49 and 51.

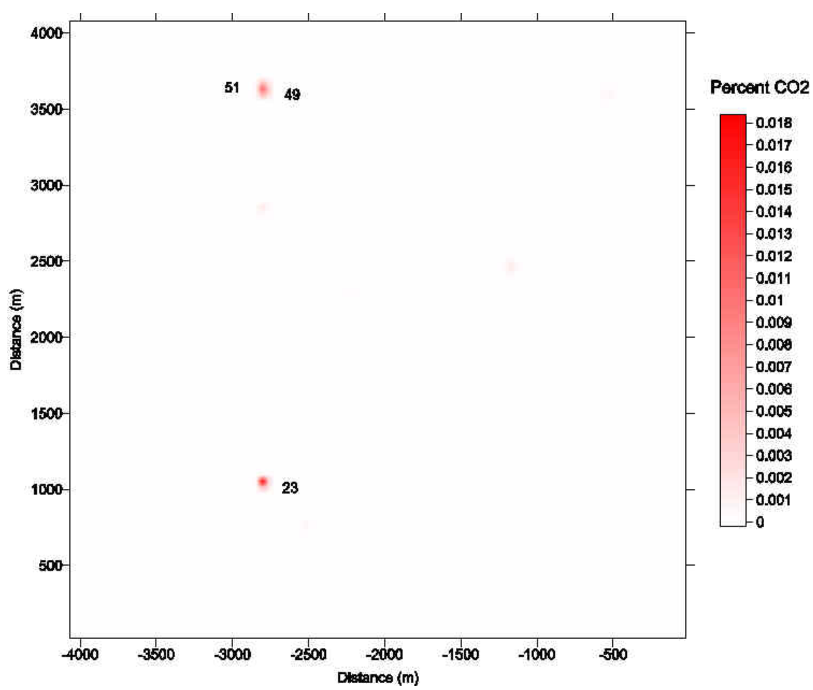

Figure 7 Basement-CO_2 concentrations after 5 years of injection.

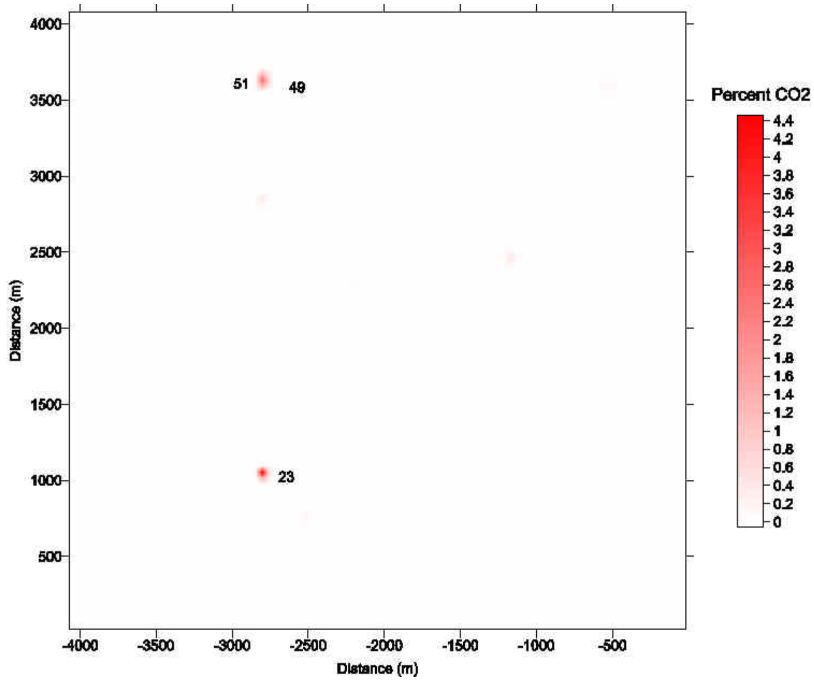

Figure 8 Soil-CO_2 concentrations after 5 years of injection.

After 20 years, the concentrations in the basements of the properties were 0.068% near well 23 and 0.095% near wells 49 and 51, the locations with the highest concentrations. Like the 5-year concentrations, these concentrations posed no risk to human receptors because they were below the threshold values. A map of the basement CO_2 concentrations is presented in Figure 9. The maximum soil concentrations (Figure 10) were 16.61% near well 23 and 23.19% near wells 49 and 51.

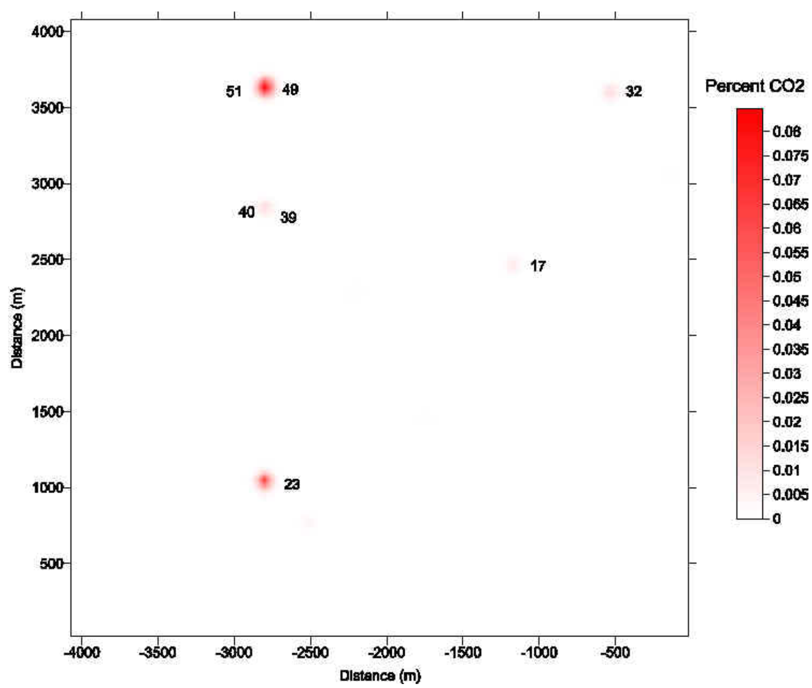

Figure 9 Basement-CO_2 concentrations after 20 years of injection.

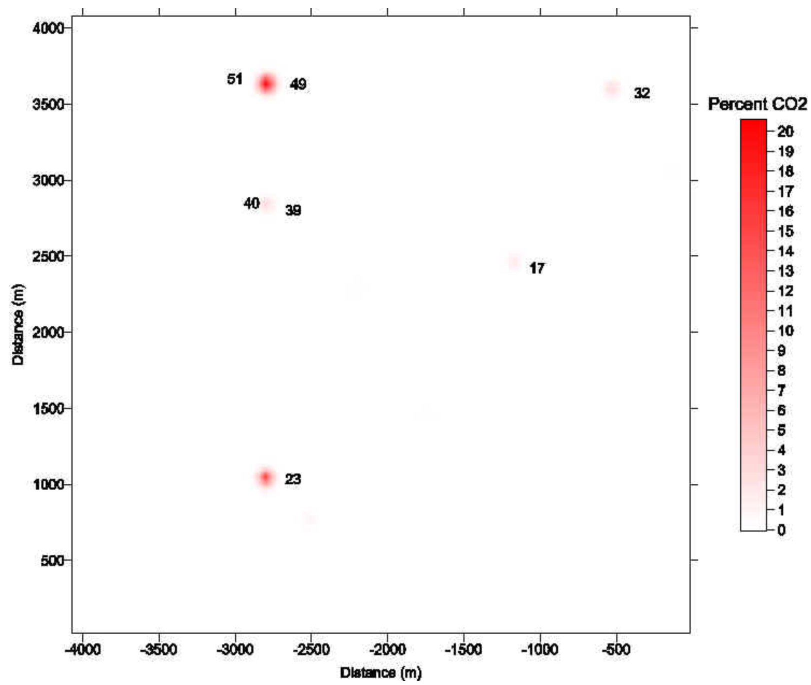

Figure 10 Soil concentrations after 20 years of injection.

Discussion

The results described above were based on a very large injection rate, 43,200 t-CO_2/day (1.58 x 10^7 t-CO_2/year), and if a more typical injection rate of 2740 t-CO_2/day (1 x 10^6 t-CO_2/year) [Korbøl and Kaddour, 1995] were used, the CO_2 concentrations would be lower. It also seems unlikely that a large sequestration operation would be allowed to take place in the vicinity of a housing development. If the development were farther from the injection site, the CO_2 concentrations would also be lower.

The calculations of the CO_2 concentration and the screening levels were simple analytical methods that could be done easily and quickly. If only a fraction of the 10,871 CO_2-emitting power plants in the United States [EIA, 2005] were to capture and sequester CO_2 on site, it seems likely that hundreds to thousands of sites would need to be permitted, and so simple and fast techniques will be needed to expedite the permitting process. However, to ensure the accuracy of the calculations, it will be important to examine the assumptions involved with the calculations.

The results presented in the paper by Altevogt and Celia [2004] showed that for a two-dimensional simulation, advection played a significant role in the transport of CO_2. Altevogt and Celia also examined the effect of density differences in the migration of CO_2 and found that density plays a significant role in the extent and amount of CO_2 in the vadose zone. Their results mean that, although a diffusion-only approach was used in this paper, it will likely be important to include advection and density in actual site models used for site permitting

The results of the simulations presented in the previous section indicated that there was no risk to humans from exposure to CO_2. However, these results are based on many assumptions, and it is important to understand how the choice of values may affect the outcome of the calculations. The variables that appear in Equations 4 and 5 are the diffusion coefficient through the soil and the cracks in the foundation, D and D^{crack}; the volumetric overturning rate of the basement, $Q_{building}$; the thickness of the foundation, L_{crack}; and the total area of the cracks in the foundation, A_{crack}. It seems unlikely that L_{crack} will vary over a large range, and A_{crack} can probably be estimated based on crack sizes in representative basements. This leaves the estimates of the diffusion coefficients and the overturning rate as the variables that may play a large role in the magnitude of the outcome.

Sensitivity analyses were conducted to examine the effect of the diffusion coefficient on the CO_2 concentration. The analyses were done for the concentrations at property 8723, which was the property with the highest concentration after 20 years and is in the vicinity of wells 49 and 51. The diffusion coefficient, D, for the soils was varied while holding all the other variables at the values previously described (Figure 11), D^{crack} was varied while holding all the other variables constant (Figure 12), and D and D^{crack} set equal to each other were varied while holding all the other variables constant (Figure 13). For each analysis the variation of the diffusion coefficient of the soil was more than two orders of magnitude, between 1×10^{-7} and 1×10^{-5} m^2/s. This is the approximate range of variation in the diffusion coefficient between clay soils and free air [Nazaroff, Moed, and Sextro, 1988].

The plot of the variation of the diffusion coefficient in the soil demonstrates that the choice of values for the diffusion coefficient is less important if the soils have a high diffusion coefficient. An error in the choice of values below 2×10^{-6} m^2/s will add much more error to the risk calculation than an error in the choice of a coefficient for a soil that has a diffusion coefficient above the 2×10^{-6} m^2/s range. It is also important to note that regardless of the value of D, the concentration in the basement of property 8723 never nears either screening level.

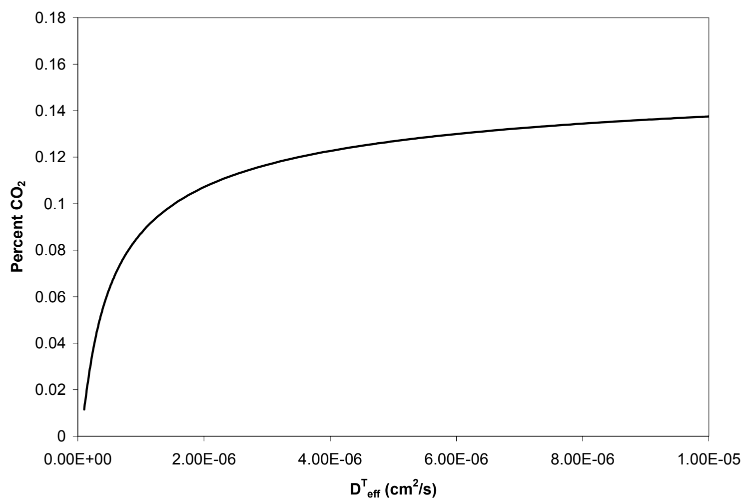

Figure 11 CO_2 concentration in property 8723 with a variation of D for the soil while holding all other variables constant.

The plot of D^{crack} versus CO_2 concentration shows the linear relationship between D^{crack} and CO_2 concentration in the basement (Figure 11). This means that an error in the magnitude of D^{crack} will lead to an error in the concentration that is linearly related to the size of the error in D^{crack}.

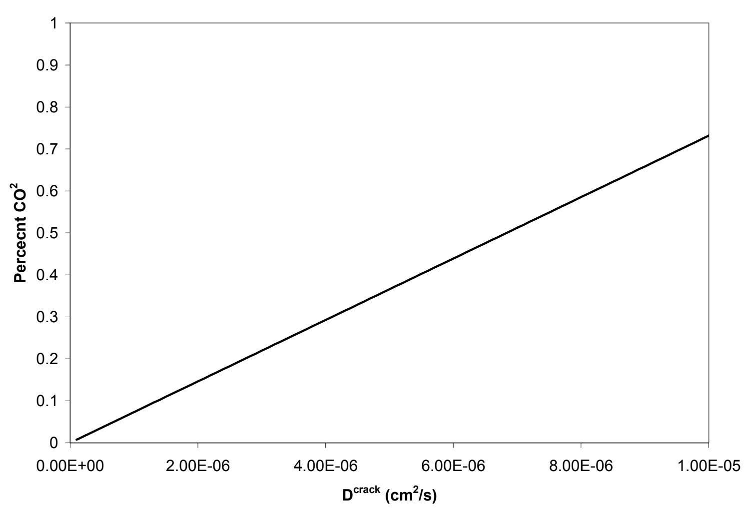

Figure 12 CO_2 concentration in property 8723 with a variation in D^{crack} while holding all other variables constant.

The plot of variation of D equal to D^{crack} shows that the concentration of CO_2 in the basement of the properties is dominated by D^{crack}; the plot appears linear after 2 x 10-6 m^2/s. Therefore, the choice of a value for D^{crack} is more critical than the choice of the value for D. Also, like the above result, an error in the magnitude of the diffusion coefficient will lead to an error in the concentration that is linearly related to the size of the error in the diffusion coefficient. It is important to point out that although the value of D^{crack} and D equal to D^{crack} makes a difference in the concentration of CO_2 in the property, none of the concentrations reaches either screening level.

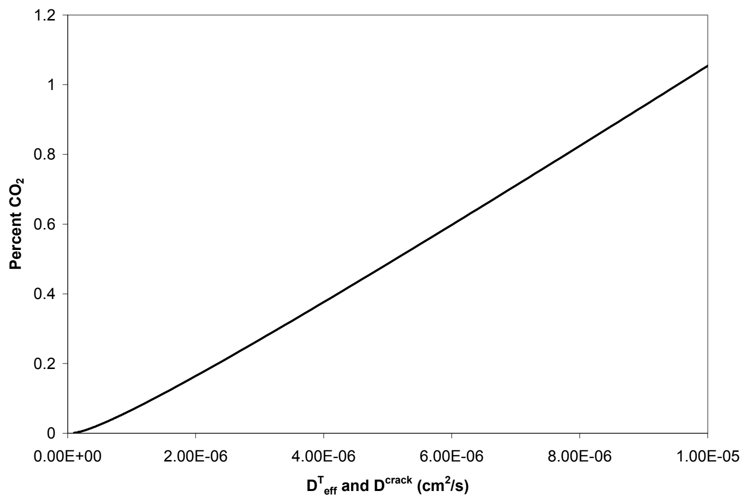

Figure 13 Variation of CO_2 concentration with variation of D when $D = D^{crack}$ with all other variables constant.

A sensitivity analysis was also conducted to study the variation of the overturning rate versus the basement CO_2 concentration (Figure 14). The results for property 8723 after 20 years of injection show that when the overturning rate becomes smaller than 0.1 $hour^{-1}$, the CO_2 concentration starts to climb rapidly. This means that unless the basement is nearly perfectly sealed, the concentrations in the basement will be diluted by air exchange. Some research on residential overturning rates has been conducted. One study for a house in Chicago [Nazaroff et al., 1985] measured overturning rates intermittently over a 4-month period between 0.10 and 0.34 $hour^{-1}$ with an average over the period of 0.22 $hour^{-1}$. In another study of houses in Rochester, New York, Nazaroff, Offerman, and Robb [1983] found that the overturning rates in houses in that area varied between 0.22 and 1.16 $hours^{-1}$ over a 6-month period. A third study found that residential air exchange rates varied between 0.250 and 1.725 $hours^{-1}$ [Bouhamra et al., 1998]. Although none of these studies found rates below 0.10 $hour^{-1}$, it is important to clarify that the rates were for complete houses and not basements.

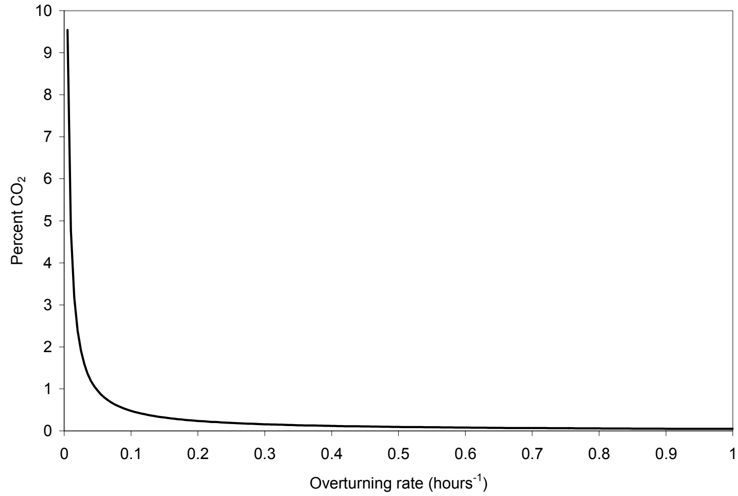

Figure 14 Variation in CO_2 concentration with changing overturning rate, holding all other variables constant.

In the case of the soil-CO_2 concentrations (Figure 15), it will be more important to have a good handle on the diffusion coefficient if the soil has a diffusion coefficient in the range of 1 x 10^{-7} to 2 x 10^{-6} m^2/s than it would be if the coefficient is above that range. In the range of 1 x 10^{-7} m2/s to 2 x 10^{-6} m^2/s, the calculated concentration is very sensitive to the value of the diffusion coefficient. The fact that there are high soil CO_2 values indicates that it will be important to have a soil and/or environmental monitoring program in place in the area of the sequestration site–for example, establishing soil gas monitoring stations in the vicinity of abandoned wells that are used regularly or setting up an aerial spectral photography program in which spectral photographs are taken on a regular basis. The upper end of the values calculated for this analysis fall into the lower end of the range of CO_2 concentrations measured in the tree kill area caused by the natural CO_2 leak at Mammoth Mountain, California [Hill and Prejean, 2005].

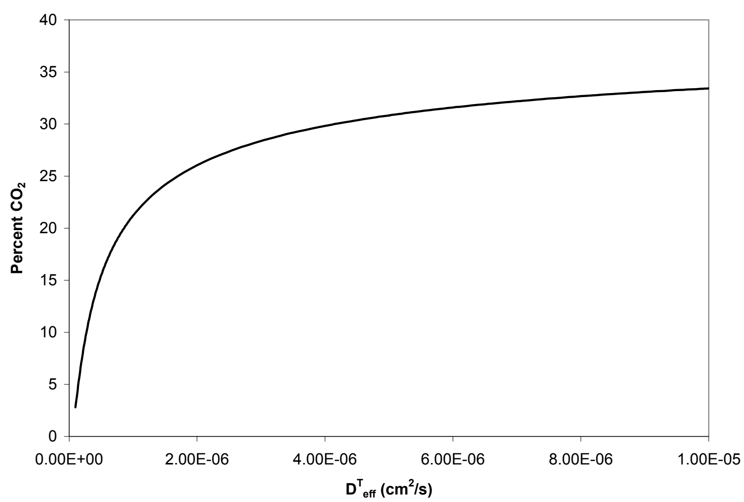

Figure 15 Variation of soil-CO_2 concentration at the center of property 8723 versus *D*.

Although all the basement CO_2 concentrations were below the screening levels in the analyses of *D* versus the basement CO_2 concentration, the levels of CO_2 in the soil were well above the levels that could cause environmental damage. This implies that future policy regarding the siting and licensing of CO_2 sequestration wells may need to deal directly with how soil-specific variables such as the diffusion coefficient and permeability are measured or estimated.

The sensitivity analysis for the overturning rate of basement air indicates that the overturning rate would have to be small (less than 0.1 $hour^{-1}$) before basement CO_2 concentrations would start to reach or surpass screening levels. Furthermore, research on residential overturning rates seems to indicate that rates that low are unlikely. However, measurements of specific basement overturning rates are needed to verify that dilution will keep basement CO_2 concentrations low. It will be important for regulators to pay close attention to the rates that may be used in future human health risk calculations–in particular, what rate is used and how it was estimated.

Class II injection wells can only be licensed for the injection of specific fluids related to the petroleum industry. If sequestration is to move outside the petroleum industry in the future, there will need to be a regulatory framework in place to enable the licensing and operation of CO_2 injection wells. It seems logical to create a new class of injection wells under the UIC program that will handle the injection of CO_2 in the subsurface for sequestration. Also, for the new class of wells, it makes sense to broaden the scope of the program to include the protection of human and environmental health as well as the protection of drinking water.

It will be important for all CO_2 sequestration wells to be evaluated and licensed under the same part of the UIC program, which will mean that once the new class is created, Class II wells will no longer cover the CO_2 being sequestered by the petroleum industry. Siting and licensing criteria for the new class of wells will have to consider not only other wells in the area but residences and businesses that may be affected. The regulations will need to be specific on how modeling parameters such as the diffusion coefficient, permeability, and basement air overturning rate are chosen. The condition of abandoned wells in the vicinity of the sequestration site may be unknown, which means it will not be possible to know which wells will leak. Therefore, the monitoring program associated with the new class of wells will have to include all abandoned wells that are in the vicinity or are expected to be in the vicinity of human receptors.

The criteria will also need to be specific about the timing of the monitoring and reporting of the site. The current Class II monitoring criteria require daily monitoring for hydrocarbon storage wells. This monitoring schedule is the most conservative and should be adopted for carbon storage and abandoned wells too. The current Class II reporting requirement of oral notification within 24 hours and written notification within 5 days should be retained. The annual report should be required not only to summarize the injection pressure and injection volume, as they do currently, but also to disclose any leaks, the cumulative amount leaked, and any remedial action taken to stop the leak.

Conclusion

The results of the models described in this paper indicate that the risk of passing out or becoming dizzy due to exposure to CO_2 in a basement is very low, well under the one in a million value that was used to establish the screening levels. Furthermore, with a lower, more typical injection rate and a greater distance between the injection well and the housing development, one would expect the risk to be even lower. Yet although the risk to humans was low, the concentration of CO_2 in the soil was high and may indicate that there is environmental risk associated with carbon sequestration. These potential risks coupled with the current regulations governing underground injection point to the need for new, more comprehensive regulations governing the subsurface sequestration of CO_2.

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